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CORONAL JET OBSERVED BY *HINODE* AS THE SOURCE OF A ^{3}He-RICH SOLAR ENERGETIC PARTICLE EVENT

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ABSTRACT

We study the solar source of the ^{3}He-rich solar energetic particle (SEP) event observed on 2006 November 18. The SEP event showed a clear velocity dispersion at energies below 1 MeV nucleon^{-1}, indicating its solar origin. We associate the SEP event with a coronal jet in an active region at heliographic longitude of W50°, as observed in soft X-rays. This jet was the only noticeable activity in full-disk X-ray images around the estimated release time of the ions. It was temporally correlated with a series of type III radio bursts detected in metric and longer wavelength ranges and was followed by a nonrelativistic electron event. The jet may be explained in terms of the model of an expanding loop reconnecting with a large-scale magnetic field, which is open to interplanetary space for the particles to be observed at 1 AU. The open field lines appear to be anchored at the boundary between the umbra and penumbra of the leading sunspot, where a brightening is observed in both soft and hard X-rays during the jet activity. Other flares in the same region possibly associated with ^{3}He-rich SEP events were not accompanied by a jet, indicative of different origins of this type of SEP event.

Subject headings: Sun: flares — Sun: particle emission — Sun: X-rays, gamma rays

1. INTRODUCTION

A type of solar energetic particle (SEP) event, often called "impulsive," shows enhancement of the ^{3}He/^{4}He ratio by orders of magnitude in comparison with that in the solar corona. Almost four decades have passed since the discovery of ^{3}He-rich SEP events (Hsieh & Simpson 1970), but we still do not clearly understand how such an anomaly is produced, apart from the general belief that it is due to solar flares as opposed to interplanetary shocks, which are responsible for large gradual SEP events (cf. Reames 1999). The poor understanding partly results from the difficulty of identifying the solar source, which tends to be a minor flare and sometimes lacks Hα emission (Reames et al. 1988; Kahler et al. 1987).

The great advances in both remote-sensing observations of the Sun and in situ measurements of energetic particles since the 1990s motivate us to revisit the origin of ^{3}He-rich SEP events. Such cross-disciplinary explorations have been started in recent years (e.g., Wang et al. 2006; Nitta et al. 2006), closely comparing solar images with in situ data. One finding from such endeavors is that coronal jets in and around active regions may be an important observational signature for ^{3}He-rich SEP events.

Coronal jets have been found by the Soft X-Ray Telescope (SXT; Tsuneta et al. 1991) on *Yohkoh* as a characteristic pattern of energy release in the solar corona (Shibata et al. 1992). They are modeled in the context of reconnection of an expanding loop with a large-scale unipolar magnetic field (Shibata et al. 1994). Heating occurs as a result of reconnection, and plasma in the lower atmosphere evaporates to form a flow. The evaporation flow is thought to explain most of these hot (>3 MK; see Shimojo & Shibata 2000) jets. At lower temperatures, data from the *Transition Region and Coronal Explorer* (*TRACE*; Handy et al. 1999) have revealed similar phenomena (e.g., Alexander & Fletcher 1999). Indeed, most of the jets so far associated with ^{3}He-rich SEP events have been observed in the extreme-ultraviolet (EUV) wavelengths. It is possible that the supersonic flow accelerated by reconnection may account for EUV jets (and Hα surges) and a subset of X-ray jets that are fast (Yokoyama & Shibata 1995; Cirtain et al. 2007).

In this Letter, we report on a ^{3}He-rich SEP event whose solar source is clearly identified with a coronal jet observed by the X-Ray Telescope (XRT; Golub et al. 2007) on board the *Hinode* satellite. We study and compare in situ and solar observations and illustrate the reasons for the link between the SEP event and the jet.

2. OBSERVATIONS

2.1. ^{3}He-*rich SEP Event*

A significant enhancement of the ^{3}He/^{4}He ratio was observed on 2006 November 18 by the Ultra Low Energy Isotope Spectrometer (ULEIS; Mason et al. 1998) on board the *Advanced Composition Explorer* (*ACE*) mission. This is shown in Figure 1*a*, where ions with energies above 400 keV nucleon^{-1} are included in the mass spectrogram. If we extend the plot shown in Figure 1*a* to include ions at lower energies, ^{3}He enrichment is found to last longer. Figure 1*b* shows the arrival time of each ion in the range of 10–70 AMU plotted versus speed^{-1}. Even though the data points deviate somewhat from a straight line, there is a clear velocity dispersion.

From Figure 1*b*, we expect the event to have soft spectra, not extending to high energies. Indeed, the Solar Isotope Spectrometer (SIS; Stone et al. 1998) did not observe ^{3}He ions above 4.5 MeV nucleon^{-1} (^{3}He fluence <0.5 [cm^2 sr MeV nucleon^{-1}]$^{-1}$). The spectra constructed from ULEIS data show ^{3}He/^{4}He to be ~0.5 between 500 and 800 keV nucleon^{-1} and ~0.1 at lower energies. Fe/O is also enhanced up to ~2 around 400 keV nucleon^{-1}.

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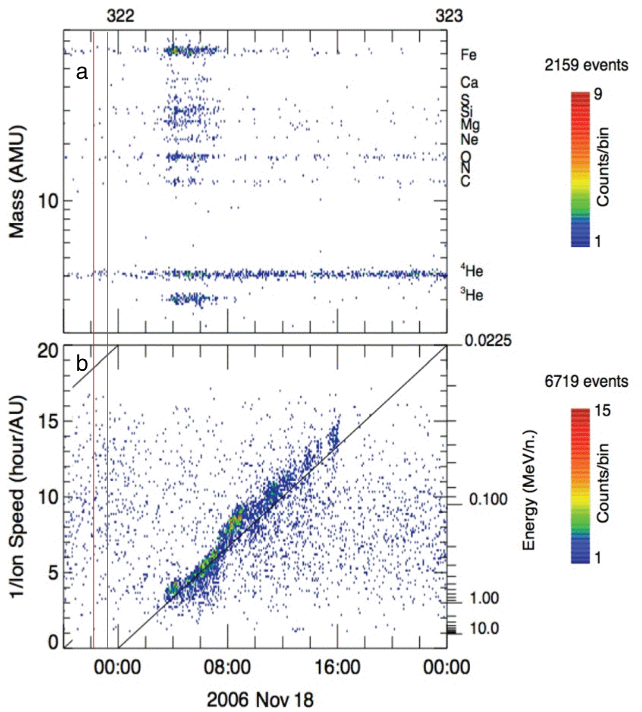

FIG. 1.—Ion data from ULEIS on *ACE* showing a ^{3}He-rich SEP event. (*a*) Mass spectrogram for elements from He to Fe for ions with energies 0.4–10 MeV nucleon^{-1}. (*b*) Ions whose mass ranges are 10–70 AMU are plotted as 1/ion speed vs. time of arrival.

2.2. *Coronal Jet*

From the velocity dispersion shown in Figure 1*b*, the injection time of the SEP event is estimated to be November 17 22:00 UT ± 2 hr. We first studied full-disk images from the Soft X-Ray Imager (SXI; Lemen et al. 2004) aboard the *GOES-13* satellite. The pixel size of these images is 5″. We made use of the ∼1 s exposure images in the Polythin filter, which had a 4 minute cadence. The only noticeable coronal activity in this time window was a jet from active region (AR) 10923 accompanying a B2.4[8] flare. At that time, AR 10923 was located at heliographic coordinates S07°W50°. Many small flares were observed from AR 10923. Their characteristics include hard X-ray coronal emission (Krucker et al. 2007) and relatively flat hard X-ray spectra (Hannah et al. 2008).

XRT took images of the region in 512 × 512 1″ pixels with a cadence of ∼95 s for each sequence. There were two sequences in Al_poly filter (later replaced by C_poly as the flare intensified) and Be_thin filter (later replaced by Be_med), which is more sensitive to high temperatures. Images in the two sequences deliver essentially the same spatial information on the jet (indicating its temperature comparable to that of the typical SXT jet), so we concentrate on the images in Al_poly.

In Figures 2*c*–2*h*, we study the development of the jet in XRT images extracted for a half of the full field of view (FOV). Figure 2*c* is an intensity image in negative before we recognize the jet. The other images are composites of the running difference for the bright area inside the AR and intensity images (in negative) outside so scaled to bring up the diffuse jet. The jet propagated to the southwest at a speed of ∼450 km s^{-1}. It also expanded to the perpendicular direction, i.e., to the northwest, similar to examples from SXT (e.g., Shibata et al. 1994). An overlay of the contours of the sunspot darkness on the basis of the continuum image from the Michelson Doppler Imager (MDI; Scherrer 1995) shows brightenings between the umbra and penumbra (marked in Fig. 2*c* by the arrow).

Note that the period of the jet activity (22:26 UT–22:32 UT) coincides with that of the series of type III bursts in both metric and longer wavelengths (Fig. 2*a*) as observed at the Learmonth Observatory, part of the US Air Force Radio Solar Telescope Network (RSTN), and by the Radio and Plasma Wave Experiment (WAVES; Bougeret et al. 1995) on *Wind*. This clearly demonstrates that the jet involved magnetic field lines that are open to interplanetary space, unlike the previously reported jets

[8] A B*n* flare has the peak flux I_{peak} of $n \times 10^{-7}$ W m^{-2} in the 1–8 Å channel of the *GOES* X-ray Spectrometer. Classes of A, C, M, and X refer to fluxes 0.1, 10, 100, and 1000 times, respectively, as intense as the B class.

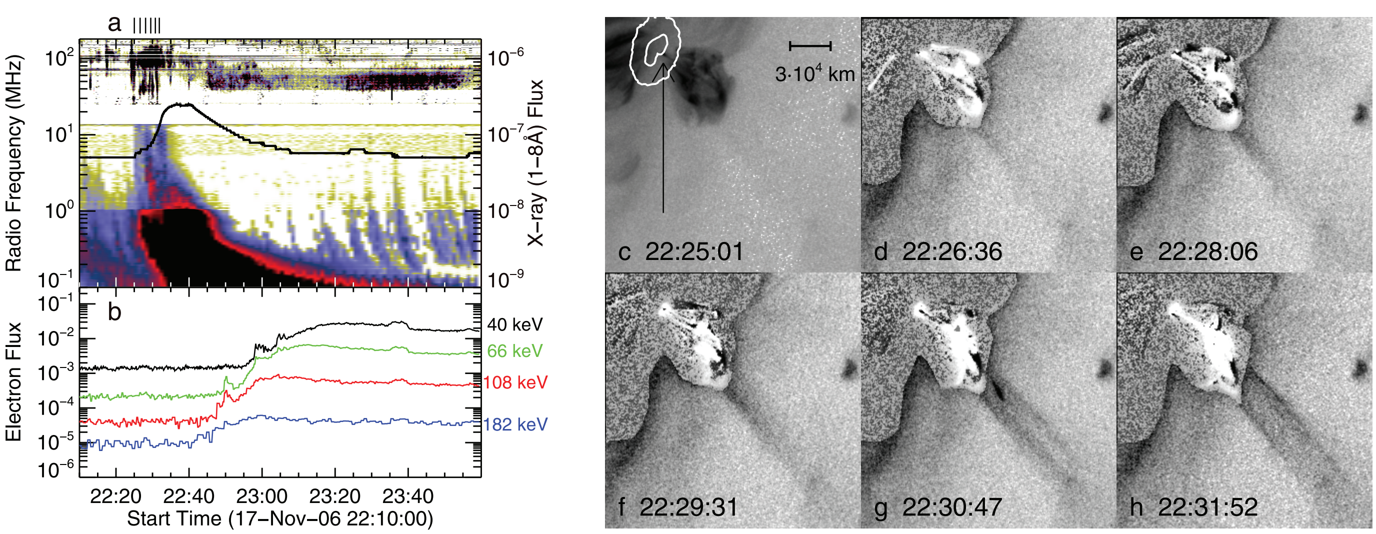

FIG. 2.—The evolution of the jet with respect to the type III bursts and the electron event. (*a*) Radio dynamic spectra and X-ray light curve. The spectra comes from Learmonth/RSTN above 25 MHz and from WAVES below 14 MHz. (*b*) The electron flux at 1 AU as observed by the solid state telescopes of 3DP. (*c*–*f*) XRT subimages (1/2 of the full FOV). Panel *c* is a direct image in negative, and panels *d*–*h* consist of running-difference images for the flare and overexposed images elsewhere to bring up diffuse features such as the jet. The image times are indicated at the top of panel *a*. The MDI white-light image at 23:59:31 is overplotted in panel *c* in contours with solar rotation corrected. The two contour levels roughly define the umbra and penumbra of the spot of AR 10923.

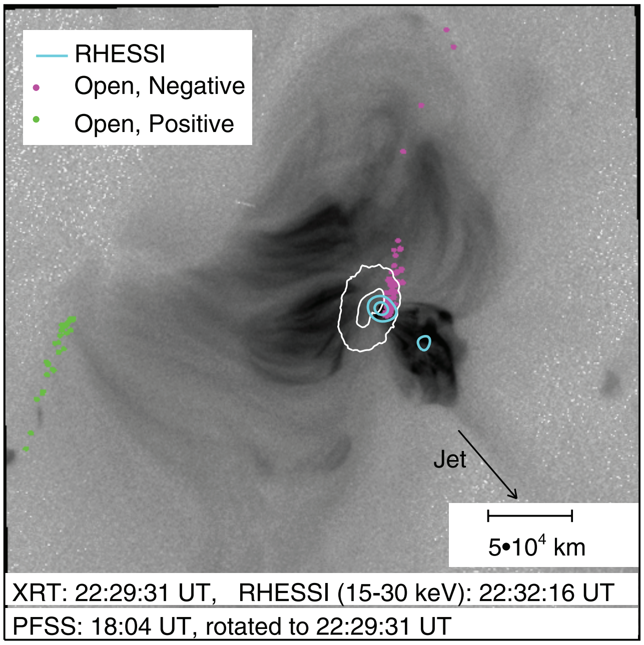

Fig. 3.—Hard X-ray sources from *RHESSI* plotted on an XRT full FOV image during the jet. Also indicated are the footpoints of the open field lines as calculated using the PFSS model.

that were observed by XRT (Shimojo et al. 2007). A nonrelativistic electron event was observed shortly after the type III bursts, as shown in Figure 2*b*, which plots the electron flux as measured by the Three-dimensional Plasma and Energetic Particles instrument (3DP; Lin et al. 1995) also on *Wind*. We calculate the release time of the first-arriving electrons to be at 22:37 UT ± 5 minutes (500 s added to be directly comparable with electromagnetic emissions observed at Earth). The link of the ^{3}He-rich SEP event with the jet is made solid by the type III bursts and the electron event (see Reames & Stone 1986; Reames et al. 1985 for the association of ^{3}He-rich SEP events with type III bursts and electron events).

2.3. *Other Related Observations*

The B-class flare associated with the jet was also observed by the *Reuven Ramaty High Energy Solar Spectroscopic Imager* (*RHESSI*; Lin et al. 2002). The event-integrated image in the 15–30 keV band (Fig. 3) has the strongest source at the boundary of the umbra and penumbra of the spot, cospatial with a brightening in soft X-rays (marked by an arrow in Fig. 2*c*). A weaker source is in the center of the bright area in soft X-rays to the southwest of the spot. The two hard X-ray sources may correspond to the footpoints of the flare loop.

In Figure 3, we also indicate the areas that correspond to the footpoints of open field lines as calculated using the potential field source surface (PFSS) model.[9] We note open flux around the hard X-ray source on the umbra-penumbra boundary.

The jet was also associated with a relatively narrow coronal mass ejection (CME) observed by the Large Angle and Spectrographic Coronagraph (LASCO; Brueckner et al. 1995). It has recently been found that these narrow CMEs are quite frequently associated with ^{3}He-rich SEP events (Kahler et al. 2001; Wang et al. 2006; Nitta et al. 2006).

2.4. *Jets and SEP Events from AR 10923*

AR 10923 produced more X-ray jets from the same area to the southwest of the spot, as clearly observed in full-disk images from the SXI on *GOES-13*. Table 1 summarizes these jets including the one described in § 2.2. They usually do not accompany a brightening detectable to the *GOES* X-Ray Spectrometer. All of them were associated with a type III burst observed by WAVES. They appear to extend to low temperatures (i.e., 1–2 MK) since they are clearly identified in EUV images from *TRACE* whenever available, although their typical short durations make it hard to detect them unambiguously in images from the Extreme Ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995) with a ~12 minute cadence. Some of them are associated with narrow CMEs, but others are not, probably reflecting, in part, the limited sensitivity of the instrument.

Only the jet on November 17 was associated with a ^{3}He-rich SEP event. The one on November 16 was associated with a much smaller electron event, but no ^{3}He injection was observed, even though the Fe/O ratio became ~1 starting around 00:00 UT on November 16 and continued through early November 21. Although there were no more jets after November 18, ^{3}He enrichment was observed during a short period (starting around 07:00 UT on November 20) and an extended period (starting around 10:00 UT on November 21). The SEP event

[9] The PFSS model used here extrapolates photospheric magnetic maps that consist of MDI magnetograms for the well-observed part of the Sun and modeled magnetograms elsewhere on the basis of the flux dispersal model. See Schrijver & DeRosa (2003) for details of actual implementation.

TABLE 1
Jets from AR 10923 Observed by SXI aboard *GOES-13* in 2006 November

Day	Time	Longitude (deg)	XRT[a]	*TRACE*[a]	Electrons[b]	Flare[c]	CME Width (deg)	CME Speed (km s^{-1})
15 ……	06:38	W14	…	Y (284 Å)	N	N	40	488
15 ……	18:46	W21	…	…	N	N[d]	No CME	
15 ……	23:10	W24	Y	Y (195 Å)	N	N	No CME	
16 ……	07:50	W29	…	…	Y	N	32	493
17 ……	22:30	W51	Y	…	Y	B2.4	64	154
18 ……	10:06	W58	Y[e]	N (1600 Å)	N	N	18	188

[a] Y: jet observed, N: no jet observed, … : no data.
[b] Y: electron event observed by the solid state telescopes of 3DP on *Wind*, N: no electron event.
[c] Based on the *GOES* X-Ray Spectrometer. The background-dependent detection threshold was (6–10) × 10^{-8} W m^{-2} in the 1–8 Å channel, i.e., A6–B1.
[d] There was a nearly simultaneous C1.8 flare in AR 10924 at S09°E30°.
[e] The jet was already fully developed in the first image after a data gap.

on November 21 includes a velocity dispersion not as clean as the one shown in Figure 1*b*, pointing to an injection at ~07:00 UT (but with large uncertainties). It also includes energy-independent increases, indicating encounters with flux tubes already filled with particles. These periods of ^{3}He enrichment were likely to be due to small flares in AR 10923, but none of them were associated with jets.

Interestingly, SIS observed ^{3}He at $\gtrsim$4.5 MeV nucleon^{-1} only later on November 21. This was probably associated with a type III burst at 19:25 UT (shortly followed by an electron event) and a simultaneous A-class flare in AR 10923 (mostly limb occulted, but again lacking a jet).

3. DISCUSSION AND SUMMARY

We have jointly analyzed a wide range of data to probe the origin of the ^{3}He-rich SEP event on 2006 November 18, finding that the coronal jet is a key to the understanding of acceleration and transport of particles including ^{3}He. This was already indicated in recent publications (Wang et al. 2006; Nitta et al. 2006), but not as convincingly as the present study. The close temporal correlation of the jet with both the type III bursts at metric to kilometric ranges and the electron event (Fig. 2) strengthens the link between the jet and the ^{3}He-rich SEP event.

The high-quality *Hinode* XRT images allow us not only to detect the jet but also to follow its spatial structure and evolution with respect to the concurrent flaring. Ignoring the complexity of small-scale brightenings (see Figs. 2*d*–2*h*), the jet and flare may be understood in terms of the model of an expanding loop reconnecting with large-scale magnetic field (see, e.g., Fig. 8 in Shimojo & Shibata 2000). As a result of reconnection, both the jet and the flare loop are produced. The hard X-ray sources are thought to mark the footpoints of the flare loop. In order for the particles to be observed at 1 AU, the large-scale magnetic field should in fact be open to interplanetary space. One possibly important aspect is that the open field is anchored at the boundary between the sunspot umbra and penumbra. While *Yohkoh* SXT observations revealed frequent occurrences of jets around sunspots (Shimojo et al. 1998), their possible relation with the sunspot field was not directly addressed. In the SEP context, we need more examples to determine if the involvement of a sunspot has any relation with ^{3}He enrichment.

Our study provides a clear link between a ^{3}He-rich SEP event and a jet, but many ^{3}He-rich SEP events are not associated with jets (such as the one on November 21 as mentioned in § 2.4). Clearly there is an issue about observational effects including a projection effect and instrument sensitivity. But there may be a different class of ^{3}He-rich SEP events and electron events that may leave no clear solar signatures, possibly because they originate in the high corona, as previously proposed for 2–10 keV electron events (Potter et al. 1980). Do the origins at different heights of the solar corona reflect in the SEP properties? We plan to address this statistically in a future study.

We thank the *Hinode*, *ACE*, *Wind*, *RHESSI*, *SOHO*, and *TRACE* instrument teams and the NGDC for making the data available and M. DeRosa for help with the PFSS extrapolations. The SXI data have been provided by the NOAA SXI project. *Hinode* is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in cooperation with ESA and NSC (Norway). We acknowledge use of the LASCO CME catalog generated and maintained at the CDAW Data Center by NASA and the Catholic University of America in cooperation with the Naval Research Laboratory. This work has been supported by NASA grant NNG05GD68G and NSF grant ATM-0454408.

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